REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

0165

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
FINAL

3. REPORT T... AND DATES COVERED
1 Dec 99 - 30 Nov 02

4. TITLE AND SUBTITLE
Coherent Structures and Chaos in Beam Plasmas

5. FUNDING NUMBERS
F49620-00-1-0007

6. AUTHOR(S)
Dr. Chiping Chen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Insitute of Technology
Plasma Science and Fusion Center
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NM
4015 Wilson Blvd, Room 713
Arlington, VA 22203-1954

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-00-1-0007

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report summarizes our research carried out tinder the auspices of the above referenced grant from December I. 1999 to November 30, 2002. The goal of this research was to investigate coherent structures and chaos in beam plasmas in regimes relevant to the development of advanced high-power microwave (HPM) sources for directed energy applications.

The report is organized as follows. In Sections 1-5, a brief summary of our research accomplishments is presented in selected areas. In Section 6, a brief description of our interactions with Air Force Research Laboratory, industries and other academic institutions is given. In Section 7, references are cited.

20030513 063

14. SUBJECT TERMS

15. NUMBER OF PAGES
21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

Final Report
Coherent Structures and Chaos in Beam Plasmas
AFOSR Grant No. F49620-00-1-0007

February 27, 2002

Submitted to:
Dr. Arje Nachman
Program Manager
Air Force Office of Scientific Research
801 North Randolph Street, Room 732
Arlington, VA 22203-1977

Submitted by
Dr. Chiping Chen
Principal Investigator
Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Tel: 617 253-8506
Fax: 617 253-6078
Email: chenc@psfc.mit.edu

Final Report
Coherent Structures and Chaos in Beam Plasmas
AFOSR Grant No. F49620-00-1-0007

This report summarizes our research carried out under the auspices of the above referenced grant from December 1, 1999 to November 30, 2002. The goal of this research was to investigate coherent structures and chaos in beam plasmas in regimes relevant to the development of advanced high-power microwave (HPM) sources for directed energy applications.

The report is organized as follows. In Sections 1-5, a brief summary of our research accomplishments is presented in selected areas. In Section 6, a brief description of our interactions with Air Force Research Laboratory, industries and other academic institutions is given. In Section 7, references are cited.

A list of researchers supported by this grant is provided.

A list of publications is provided at the end of this report.

1. Determination of the Current Limit on the Confinement of Bunched Pencil Beams in High-Power Relativistic Klystrons (Hess, 2002; Hess and Chen, 2000 and 2000b)

Under the auspices of the grant (Chen, 1999), we developed theory for the confinement of a highly bunched pencil beam propagating through a perfectly conducting drift tube in a uniform magnetic field (Hess, 2002; Hess and Chen, 2000), and extended it to include the effects of periodic permanent magnet focusing and rf fields (Hess, 2002; Hess and Chen, 2002b). By applying the extended theory, we gained, for the first time in history, a basic understanding of electron beam losses in high-power periodic permanent magnet (PPM) focusing klystrons during their full-power operation (; Hess, 2002; Hess and Chen, 2002b).

In particular, by analyzing the Hamiltonian dynamics of a train of collinear periodic point charges interacting with a conducting drift tube, an rf field, and an applied PPM focusing field, a space-charge limit was discovered for the radial confinement of highly bunched electron beams, which was shown to be significantly below the well-known Brillouin density limit for an unbunched beam. Several state-of-the-art PPM klystrons developed at SLAC (Sprehn, et al., 1998; Sprehn, et al., 2000; G. Scheitrum, 2002) were found to operate close to or above this limit, shedding some light on the origin of observed beam losses (Sprehn, et al., 1998; Sprehn, et al., 2000; G. Scheitrum, 2002).

For the radial confinement of the center of mass of a strongly bunched train of electron clouds in a PPM focusing klystron, the space charge limit was shown to be (Hess, 2002; Hess and Chen, 2000b)

$$\frac{8c^2 I_b}{\omega_{c,rms}^2 a^2 I_A} \leq \left[1+\sum_{n=1}^{\infty}\frac{n\alpha}{I_0(n\alpha)I_1(n\alpha)}\right]^{-1}, \tag{1.1}$$

or approximately (for $\alpha < 2$)

$$\frac{8c^2 I_b}{\omega_{c,rms}^2 a^2 I_A} \leq \frac{\alpha}{\pi}, \tag{1.2}$$

where $I_b = Nef$ is the average current in the klystron (in amperes), $I_A = \gamma_b \beta_b m_e c^3 / e \cong \gamma_b \beta_b \times 17\,\text{kA}$ is the electron Alfven current, $\omega_{c,rms} = eB_{rms}/m_e c$, and $\alpha = 2\pi a f / \gamma_b \beta_b c$. Note that the left-hand side of Eq. (1.1) or Eq. (1.2) is equal to the self-field parameter $2\omega_p^2/\omega_{c,rms}^2$ in the rest frame, where $\omega_p^2 = (4\pi e^2/m_e)(N/\pi a^2 L_{rest})$ is the effective plasma frequency squared. Figure 1.1 shows a plot of the right-hand side of Eq. (1.1) versus the parameter α.

We applied the beam confinement condition in Eq. (1.1) [or Eq. (1.2)] to three recent PPM focusing klystron experiments at SLAC, namely, the X-band 50-MW XL-PPM (Sprehn, et al., 1998) and 75-MW XP (Sprehn, et al., 2000) klystrons and the W-band Klystrino (Scheitrum, 2002). The parameters for all three klystrons are listed in Table 1.1, and their operating points are marked with letters a, b and c in Fig. 1.1, respectively. As shown in Fig. 1.1 and Table 1.1, all three klystrons operated near the self-field parameter limit.

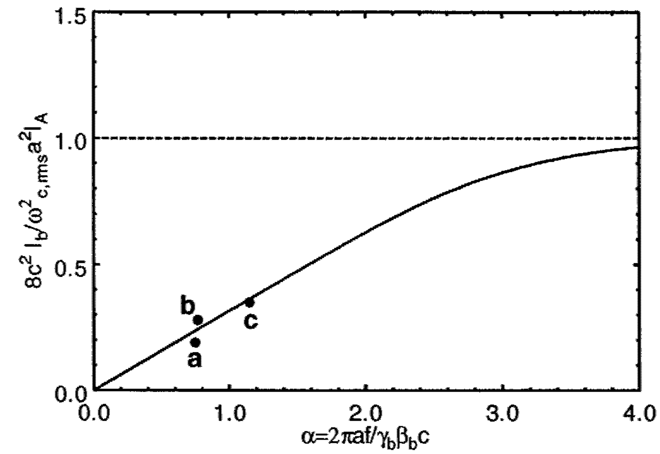


Figure 1.1: Plot of the space charge limits for the confinement of unbunched (dashed curve) and bunched (solid curve) beams as a function of α (Hess, 2002; Hess and Chen, 2002b). Here, letters a, b and c indicate experimental operating points of the 11.4 GHz 50 MW XL-PPM (Sprehn, et al., 1998) and 75 MW XP (Sprehn, et al., 2000) klystrons and the 95-GHz Klystrino (Scheitrum, 2002), respectively.

Table 1.1. Parameters for SLAC PPM Focusing Klystrons

PARAMETER	50 MW XL-PPM	75 MW XP	KLYSTRINO
f (GHz)	11.4	11.4	95
I_b (A)	190	257	2.4
γ_b	1.83	1.96	1.22
B_{rms} (T)	0.20	0.16	0.29
a (cm)	0.48	0.54	0.04
α	0.75	0.77	1.15
$\left.\frac{8c^2 I_b}{\omega^2_{c,rms}a^2 I_A}\right\rvert_{exp}$	0.19	0.28	0.35
$\left.\frac{8c^2 I_b}{\omega^2_{c,rms}a^2 I_A}\right\rvert_{cr}$	0.238	0.244	0.366

Although the 50-MW klystron (Sprehn, et al., 1998) operated slightly below the confinement limit, a mild beam loss still occurred in this device through beam halo formation as reported previously (Chen and Pakter, 2000; Pakter and Chen, 2000a; Chen, Hess and Pakter, 2000). The 75-MW XP klystron (Sprehn, et al., 2000) operated above the confinement limit. This suggests that the 75-MW klystron had greater beam loss than its 50 MW counterpart, which was consistent with the more pronounced X-ray emissions measured at the output section of the device (Sprehn, et al., 2000). The beam loss was so high that the 75-MW klystron could not achieve about one tenth of the designed repetition rate of 120 Hz for accelerator applications.

The W-band Klystrino experiment at SLAC (Scheitrum, 2002), which is currently funded under an MURI program on innovative vacuum electron device research managed by Dr. Robert Barker of AFOSR, is an important research project that interests the AFRL's HPM program in the millimeter wavelength regime. The Klystrino design parameters (Scheitrum, 2002) fall just below the theoretical limit, suggesting a marginally stable beam-wall interaction. Indeed, the initial experimental testing results (Scheitrum, 2002) showed severe beam losses and serious damage of the rf circuit by the intense bunched electron beam.

The current limit in Eq. (1.1), which is perhaps the simplest answer one could ever get to such a complex problem, applies to highly (very tightly) bunched beams. Finding the current limit in the transition from an unbunched (dc) beam to a very tightly bunched beam is of particular interest to experimentalists (see, for example, Haworth, Kendricks and Spencer, 2002), because it enables an experimentalist to measure where the current limit is reached in a device and to control the beam loss. We will analyze this transition and continue our close consultation with the experimentalists (Sprehn, Scheitrum and Caryotakis) at SLAC to improve their designs of both the X-band klystrons and W-Band Klystrinos, which will be carried out under the auspices of a pending grant (Chen, 2002).

2. Determination of the Current Limit on the Confinement of Buchend Annular Beams in HPM Tubes (Hess, 2002; Hess and Chen, 2002a)

The tremendous success in our understanding of the confinement of highly bunched pencil beams (Hess, 2002; Hess and Chen, 2000 and 2002b) has motivated us to extend our Green's function analysis to the case of highly bunched annular beams which are widely employed in the experiment HPM work at AFRL in Albuquerque (Hendricks, et al., 1996 and 1998, Agee and Gaudet, 2000; Hendricks, 2002) and elsewhere, such as the Los Alamos National Laboratory (LANL) (Fazio, et al., 1994) and the University of New Mexico (UNM) (Hegeler, et al., 1998).

Under the auspices of the grant (Chen, 1999), we analyzed the azimuthally invariant fluid equilibrium for a periodic strongly bunched charged annular beam with a negligibly small longitudinal thickness but an arbitrary radial density profile inside of a perfectly conducting cylinder and an external constant magnetic field (Hess, 2002; Hess and Chen, 2002a). The electric and magnetic fields, which were utilized in the equilibrium solution, were computed self-consistently using an electrostatic Green's function technique in the longitudinal rest frame of the beam. An upper bound on the maximum self-field parameter, which allows beam equilibrium, was obtained.

In terms of the effective self-field parameter, the space-charge limit for the bunched annular beam was shown to be (Hess, 2002; Hess and Chen, 2002a)

$$\frac{2\omega_p^2}{\omega_c^2} \le \frac{1}{\Gamma_{\max}}. \tag{2.1}$$

In Eq. (2.1), $\omega_p = \left(4\pi N_b e^2 n_b / m_e\right)^{1/2}$ is the *effective* plasma frequency in the rest frame of the beam, $n_b = \left(\pi a^2 \gamma_b L\right)^{-1}$ is the effective bunch density in the rest frame of the beam, and Γ_{max} is the maximum value of the normalized self-electric field $\Gamma(r) = -LE^{self}(r)a^2/2rN_b e$ in the radial direction, which includes the full effects of induced charges on the conducting wall.

The function $\Gamma(r)$ only depends on the geometric parameters of the system, such as the bunch spacing, the conductor radius, and the inner and outer wall radii of the annular electron beam. Figures 2.1(a) and (b) show, respectively, the density profile and normalized self-electric field $\Gamma(r)$ for a typical bunched annular beam, calculated using 200 eigenmodes.

By computing the maximum values of $\Gamma(r)$ over the entire geometric parameter space accessible experimentally, we obtained a universal current limit shown in Fig. 2.2, where constant contours of the normalized beam current defined as $\hat{I}_b = \left(4c^3 / \pi f \omega_c^2 a^3\right)\left(I_b / 17 \text{ kA}\right)$ are plotted in the accessible geometric parameter space.

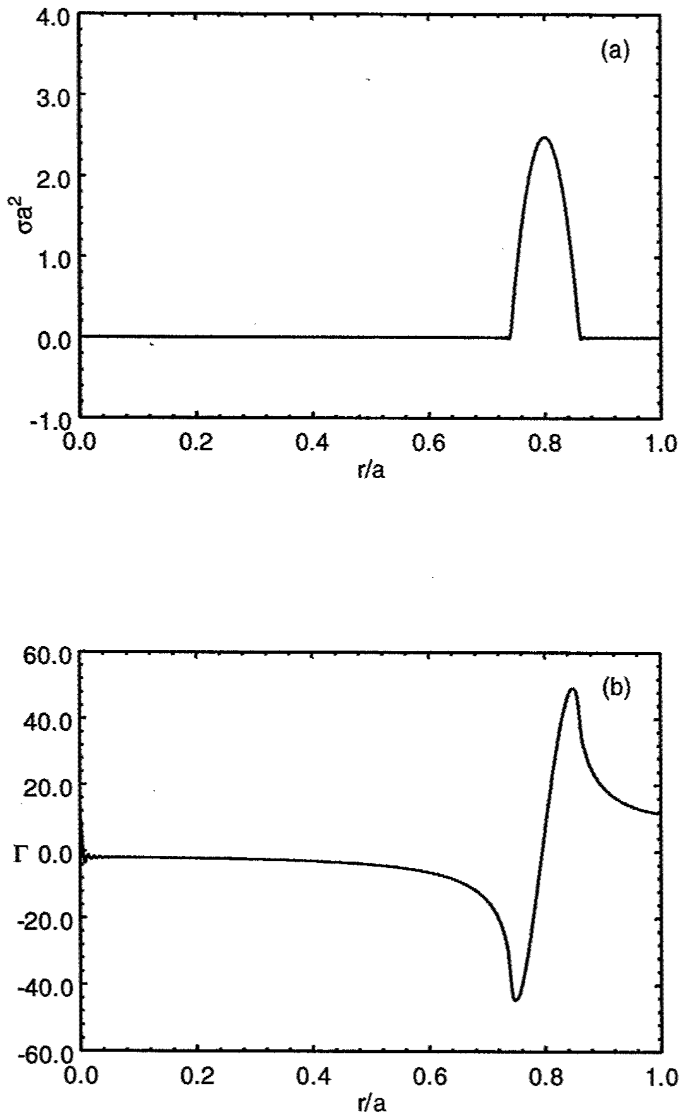


Figure 2.1 Plots of (a) quadratic beam density function versus normalized radius for an annular beam centered at r/a=0.8, (b) Γ versus normalized radius for the annular beam in (a). Here, 200 eigenmodes are used in the calculation (Hess, 2002; Hess and Chen, 2002a).

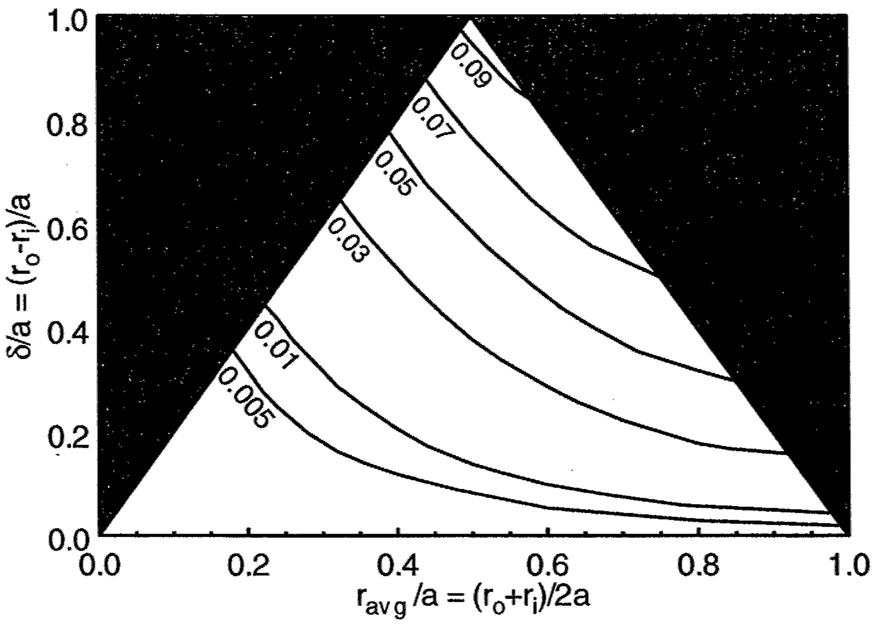


Figure 2.2 Universal plot of the current limit for the confinement of bunched annular beams. Here, a is the conductor radius, r_i and r_0 are inner and outer beam radii, respectively, and constant contours present the maximum values of the normalized beam current defined as $\hat{I}_b' = (4c^3 / \pi f \omega_c^2 a^3)(I_b / 17\ \mathrm{kA})$ for beam confinement. The gray regions are experimentally inaccessible.

Table 2.1. Parameters of Three Annular Beam HPM Devices

PARAMETER	**RKA**	**RKO**	**BWO**
f (GHz)	1.3	1.3	9.4
I_b (kA)	6.0	10.0	3.0
γ_b	2.1	2.0	1.7
B_0 (T)	0.5	0.8	2.0
r_i (cm)	2.70	6.60	0.90
r_o (cm)	3.20	7.10	1.15
a (cm)	3.65	7.65	1.28
α	0.54	1.20	1.83
$\left.\dfrac{8c^2 I_b}{\omega_{c,rms}^2 a^2 I_A}\right\vert_{exp}$	0.0133	0.0021	0.0045
$\left.\dfrac{8c^2 I_b}{\omega_{c,rms}^2 a^2 I_A}\right\vert_{cr}$	0.0126	0.016	0.059

We compared the theoretical predictions with the LANL 1.3 GHz Relativistic Klystron Amplifier (RKA) experiment (Fazio, et al., 1994), the AFRL 1.3 GHz Relativistic Klystron Oscillator experiment (Hendricks, et al., 1996 and 1998), and the UNM 9.4 GHz Backward Wave Oscillator (BWO) experiment (Hegeler, et al., 1998).

The system parameters, together with the experimental and critical values of the self-field parameter, are listed in Table 2.1 for all three experiments. Of particular interest is the LANL RKA experiment that was intended for long-pulse operation. However, beam loss, beam halo formation, and rf pulse shortening were observed (Fazio, et al., 1994). We found that the RKA experiment operated slightly above the effective self-field parameter limit in Eq. (2.1) and Table 2.1. This explains the rf pulse shortening observed in the LANL RKA experiment (Fazio, et al., 1994). It also suggests several methods that the LANL group could utilize in order to avoid beam loss and rf pulse shortening in their ongoing RKA experiment (Stringfield, 2002).

As shown in Table 2.1, the AFRL RKO experiment operated well below the theoretical current, which is in agreement with neither rf pulse shortening nor beam loss observed in the experiment (Hendricks, et al., 1998).

Although the UNM BWO experiment operated well below the theoretical current, as shown in Table 2.1, a large amount (40%) of beam loss was observed (Hegeler, et al., 1998). However, it is unclear at present time whether the beam loss in the UNM BWO experiment was due to poor vacuum, or possible azimuthal instabilities, or effects of relativistic transverse motion.

3. Relativistic Correction to the Current Limit on the Confinement of Bunched Annular Beams in HPM Tubes (Hess and Chen, 2003)

The results discussed in Sec. 2 were obtained in a non-relativistic treatment of the transverse motion of the bunched annular beam. In the analysis, we employed a self-consistent fluid equilibrium model for periodic radially symmetric bunched annular electron beams propagating in a perfectly conducting cylindrical pipe with an external magnetic focusing field present. The model assumed that the electron bunches had an arbitrary transverse density profile and negligible thickness in the longitudinal direction. The electric field was calculated self-consistently in the presence of the conductor pipe using a Green's function technique. A major limitation of this model was that it assumed that the transverse flow velocity was non-relativistic.

We now find that this assumption is not applicable for modeling high-current bunched electron beams, because bunching of a relativistic, large-annular beam induces relativistic transverse motion. (This is a new effect as far as we could identify.) In general, the transverse flow velocity may be of the order of the speed of light, and hence, relativistic effects may be important. Electron flow velocities near the speed of light will generate self-magnetic fields, which are of the order of the self-electric fields.

Recently, we have developed a more complete bunched annular beam model which incorporates all of the effects of the previous model, as well as the relativistic electron flow velocity and self-magnetic fields in the presence of the conductor pipe. This new model has led to both a better prediction of critical current limits, as well as the discovery of a fundamentally new phenomenon which limits the electron beam equilibrium current.

In particular for the parameters used in the AFRL 1.3 GHz RKO experiment operating at 10.0 kA (Hendricks, et al., 1996 and 1998), the non-relativistic model predicts a critical current limit at approximately 76.2 kA. However, the relativistic model predicts a critical current limit at 7.68 kA which is much closer to the experimental value (Hendricks, et al., 1996 and 1998). The physical mechanism which leads to the critical limit is also completely new. In the non-relativistic model, the critical limit occurred when the fast and slow equilibrium rotation solutions merged at a point within the beam. In the relativistic model, the fast and slow solutions remain separated, but the self-generated magnetic field "drills" a hole into the total magnetic field until it creates a zero field magnetic cusp at one point in the beam.

Figure 3.1 shows a plot of the self-magnetic field, for different beam currents, as a function of radius (normalized to the pipe radius) within the beam's cross-section. We believe that beam equilibrium may be inaccessible beyond the new magnetic cusp limit.

A paper is being prepared to report our latest findings (Hess and Chen, 2003).

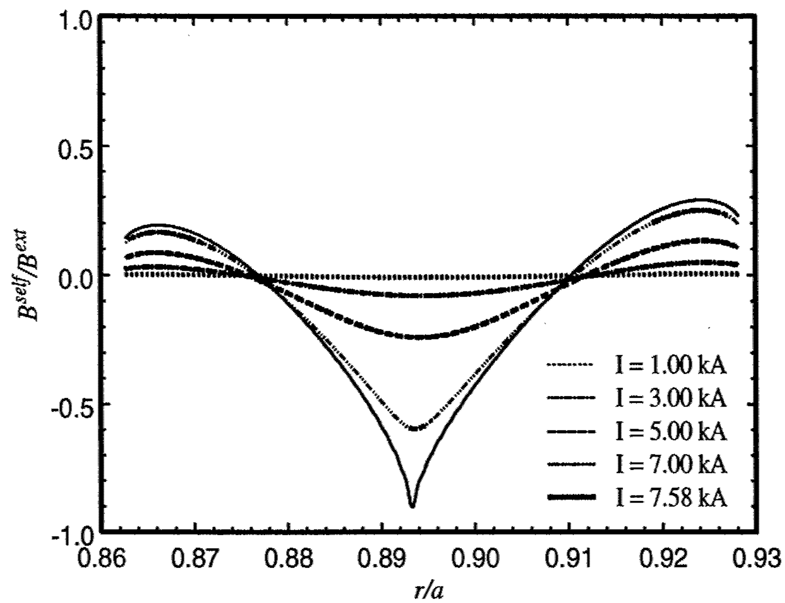


Figure 3.1: Plot of the self-magnetic field normalized to the external magnetic field as a function of normalized radius for different values of the beam current.

4. Discovery of Global Photonic Band Gaps in Metallic Photonic Crystals (Smirnova, et al., 2002)

In high-power microwave devices, the interaction of an intense electron beam with an rf circuit is employed. In moderately or highly overmoded resonators of devices such as sheet-beam klystrons, coaxial klystrons, gyrotrons and crossed-field devices, the problem of mode competition arises. To obtain high-efficiency, single-mode excitation of microwaves, the rf circuit must be selective with respect to the operating mode, and the unwanted oscillations must be suppressed. The use of photonic band gap (PBG) structures, in particular 2D PBG structures (see Figure 4.1), has been experimentally shown (Sirigiri, et al., 2001) to be a promising approach to the realization of mode selective circuits.

Under the auspices of the present grant (Chen, 1999), we took an initiative to develop a Photonic Band Gap Structure Simulator (PBGSS) code (Smirnova and Chen, 2000 and 2001; Smirnova, et al., 2002) to explore extensively the wave propagation and band gaps in metallic and/or dielectric crystals. This initiative proved to be worthwhile and began paying off in a big way, leading to two inventions (Chen, et al., 2001a and 2001b).

We discovered, via extensive PBGSS simulations, the fundamental and higher frequency global photonic band gaps (Smirnova, et al., 2002) for transverse electric (TE) and transverse magnetic (TM) modes in photonic band gap (PBG) structures consisting of two-dimensional (2D) square and hexagonal lattices of perfectly conducting cylinders.

As an example, Fig. 4.2 shows global band gaps for the hexagonal lattice, as well as the operating point of the MIT PBG gyrotron experiment (Sirigiri, et al., 2001). The global photonic band gaps in the metallic lattice, which are found to differ qualitatively as well as quantitatively from those in dielectric lattices, not only explain the observations of single-mode confinement and high mode selectivity in recent microwave PBG experiments, and but also provide a useful guide for designing metallic PBG-based devices in the future.

The properties of the global photonic band gaps are especially useful in designing PBG vacuum electronics devices. MIT's Technology Licensing Office filed on our behalf two US patent applications for PBG related devices (Chen, et al., 2001a) and PBG design software (Chen, et al., 2001b).

On the request of Dr. Delmar Barker and his coworkers at Raytheon Company (Barker, 2000 and 2002), we provided several versions of the PBGSS code which the Raytheon's research staff found to be useful in their PBG projects.

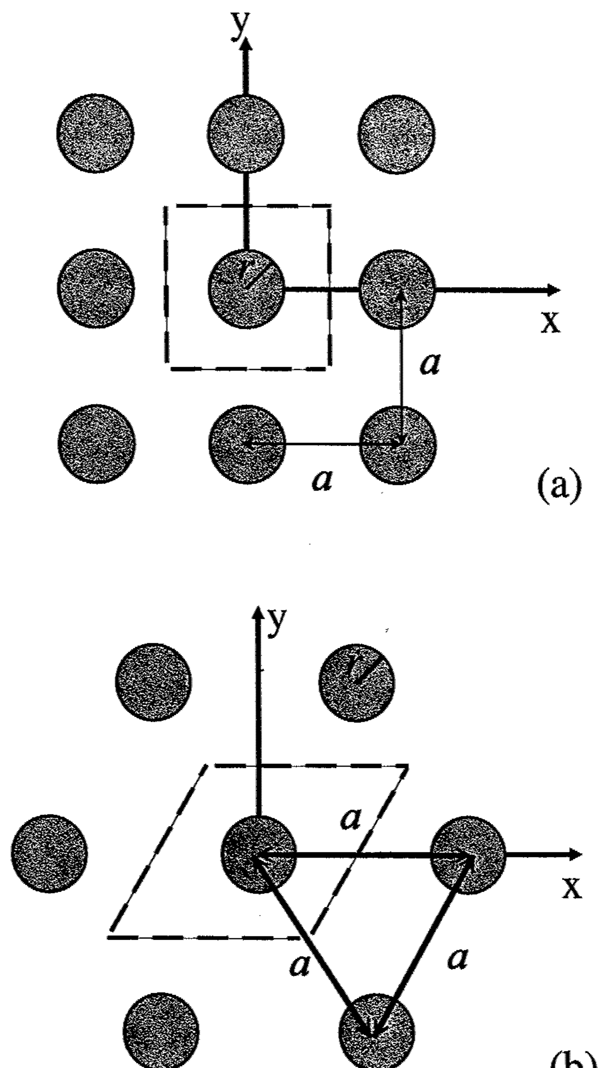
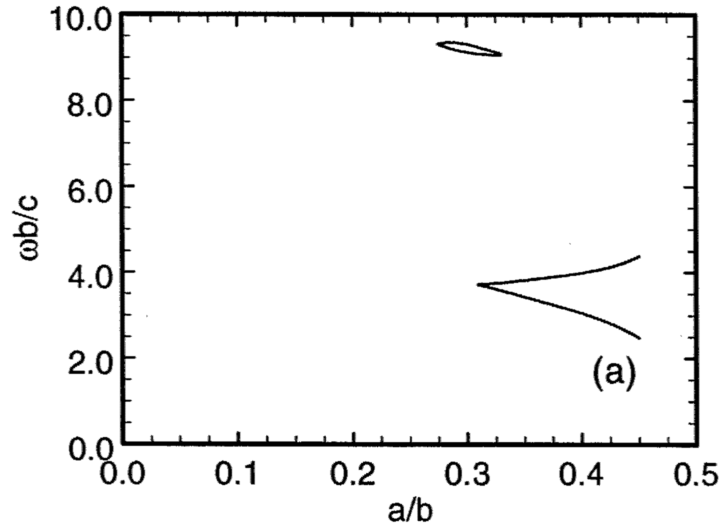


Figure 4.1: Schematic diagrams of (a) square lattice and (b) hexagonal lattice in 2D. Here, the cylindrical rods can be either dielectric or metallic (Smirnova, et al., 2002).



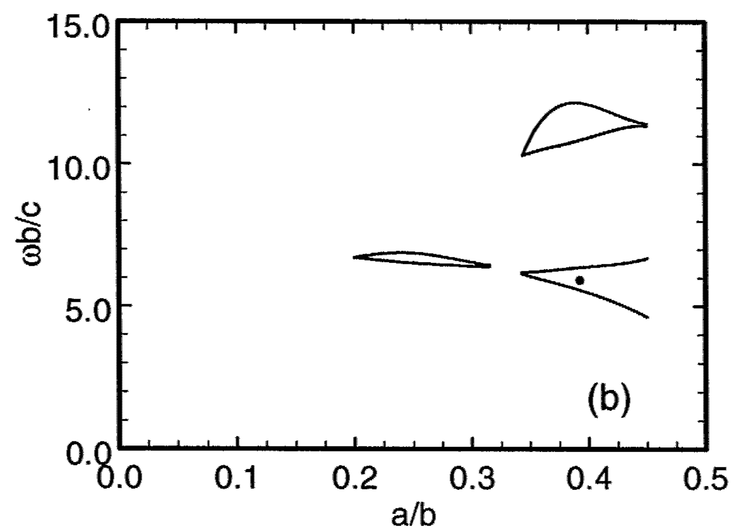


Figure 4.2: Plots of global frequency band gaps for the TE mode as a function of a/b obtained from PBGSS calculations (Smirnova, et al., 2002) for (a) square lattice and (b) hexagonal lattice. Here, the solid dot represents the operating point of the MIT 140 GHz PBG resonator gyrotron experiment (Sirigiri, et al., 2001). For the square lattice, the first-order global band gap occurs between the lowest two curves, and the second-order global band gap occurs inside of the island. For the hexagonal lattice, the first global band gap occurs between the lowest two curves, and the second- and third-order global band gaps occur inside of the lower and upper islands, respectively.

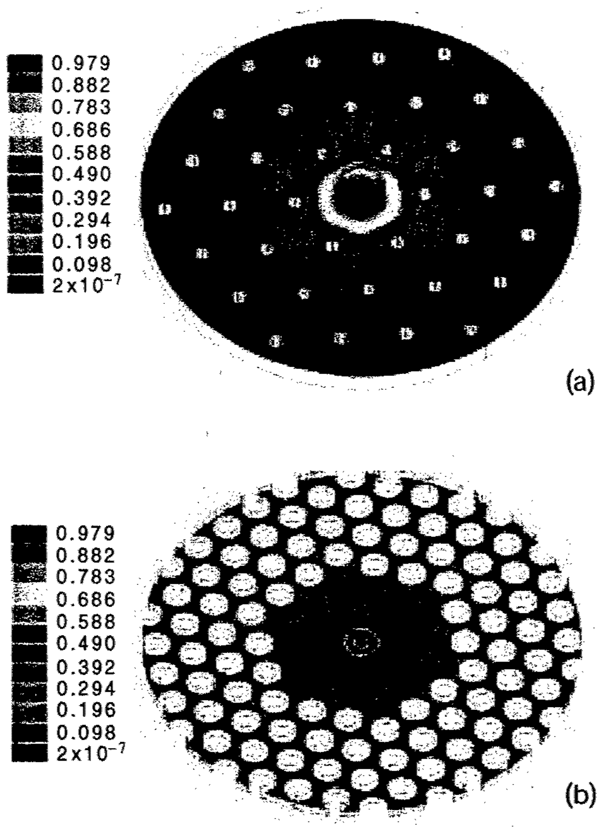


Figure 4.3: The relative magnitude of the electric field in a mode confined in PBG cavity as obtained from the HFSS simulations for (a) TM_{010}-like mode at 17 GHz, and (b) TE_{041}-like mode at 140 GHz (Smirnova, et al., 2002).

5. Other Research Topics (Otto, et al., 2001; Davies and Chen, 2001; Zhou, et al., 2003)

Under the auspices of the present grant (Chen, 1999), we also conducted research on sheet electron beam equilibrium (Otto, et al., 2001) with a large-aspect-ratio elliptical cross sections in the direction of beam propagation, which belongs to a general class of corkscrewing elliptic beam equilibria (Pakter and Chen, 2000b; Chen and Pakter, 2000), as well as on the effect of momentum spread (Davies and Chen, 2001) on the cyclotron maser instability in a spatiotemporally gyrating relativistic electron beam (Davies and Chen, 2000). Results of our research on these two topics are described in two preprints of conference proceedings at the end of this research proposal.

In addition, we have shown in a test particle model (Zhou, et al, 2003) that image-charge effects induce a new mechanism for chaotic particle motion and halo formation in an intense charge-particle beam propagating through an alternating-gradient focusing channel with a small-aperture, circular, perfectly conducting pipe. This mechanism occurs for a well-matched beam with the Kapchinskij-Vladimirskij distribution. While it is unclear how these findings will impact the HPM research, they are very important to many high-current accelerators that are being built for basic scientific research in high-energy and nuclear physics.

6. Interactions with Air Force Research Laboratory, Industries and Other Academic Institutions

Over the past year, we enjoyed the growth, depth and breath of our HPM research, and had fruitful interactions with many DOD Labs (especially AFRL), industries, and other academic institutions.

We made numerous contacts with researchers (e.g., Dr. Tom Spencer, Dr. Michael Haworth and Dr. Kyle Hendricks) at Air Force Research Laboratory and communicated our research results with them, through an informational meeting at Air Force Research Laboratory (Albuquerque, May 11, 2002) and many technical conferences such as ICOPS2002 (Banff, Canada, May 27-30, 2002) and APS DPP2002 (Orlando, November 11-15, 2002).

We collaborated with Dr. Lars Ludeking and Dr. Richard Smith of Mission Research Corporation (MRC) to conduct an AFOSR funded Phase II STTR research on crossed-field amplifiers managed by Dr. Robert Barker. We obtained new theoretical results that may help reducing turbulence and phase noise in crossed-field amplifiers such as those used in the Aegis Radar.

We made numerous contacts with researchers (e.g., Dr. George Caryotakis, Dr. Daryl Sprehn, Dr. Glenn Scheitrum and Dr. Sami Tantawi) at the Stanford Linear Accelerator Center and communicated our research results on beam confinement with them.

We also established collaboration with Dr. Lawrence Ives and his colleagues at Calabazas Creek Research, Incorporated on their high-power multi-beam klystron (MBK) project, in an effort to develop a basic understanding of bunched beam confinement in MBK.

We made efforts to advance the science and technology of photonic band gap (PBG) structures in wide areas. We won a High-Energy Laser Multidisciplinary Research Initiative (HEL MRI) Award with University of Arizona and several private companies to develop PBG-based fiber and semiconductor lasers. We also won an STTR Phase I Award with Tech-X Corporation to develop modeling capabilities for PBG structures. We initiated research collaboration with Dr. Delmar Barker and his colleagues at Raytheon Missile Systems in Tucson to explore the possibility of building a matter-antimatter trap.

7. References

Agee, F. J., and J. A. Gaudet, 2000, "Progress in high power microwave (HPM) basic research at the Air Force Research Laboratory (AFRL)," in *Intense Microwave Pulses VII*, edited by H. E. Brandt, SPIE Proc. **4031**, 2.

Barker, D. L., 2000, Raytheon Company, private communications.

Barker, D. L., 2002, Raytheon Company, private communications.

Chen, C., 1999, "Coherent structures and chaos in beam plasmas" Research proposal funded by AFOSR under Grant No. F49620-00-1-0007, Chiping Chen, Principal Investigator; and references therein.

Chen, C., 2002, "Coherent structures and chaos in high-power microwave sources" Research proposal to be funded by AFOSR, Chiping Chen, Principal Investigator.

Chen C., and R. Pakter, 2000, "Mechanisms and control of beam halo formation in Intense microwave sources and accelerators," (**Invited Paper**), Phys. Plasmas **7**, 2203.

Chen, C., M. Hess, and R. Pakter, 2000, "Electron beam halo formation in periodic permanent focusing klystron amplifiers," in *Intense Microwave Pulses VII*, edited by H. E. Brandt, SPIE Proc. **4031**, 34.

Chen, C., M. A. Shapiro, J. R. Sirigiri, and R. J. Temkin, 2001a, "Vacuum Electron Devices with a Photonic Bandgap Structure," US Provisional Patent Application, Serial No. 60/278,131, March 23.

Chen, C., E. I. Smirnova, M. A. Shapiro, J. R. Sirigiri, and R. J. Temkin, 2001b, "Photonic Bandgap Structure Simulator," US Provisional Patent Application, Serial No. 60/298,434, June 15.

Davies, J. A., and C. Chen, 2001, "Influence of velocity spread on cyclotron masers driven by spatiotemporally gyrating electron beams," in *Intense Microwave Pulses VIII*, edited by H. E. Brandt, SPIE Proc. **4371**, 39.

Davies, J. A., and C. Chen, 2000, "Stimulated radiation from spatiotemporally gyrating relativistic electron beams," Phys. Plasmas **7**, 4291.

Fazio, M. V., W. B. Haynes, B. E. Carlsten, R. M. Stringfield, 1994, IEEE Trans. Plasma Sci. **PS-22**, 740.

Haworth, M. D., K. J. Hendricks, and T. A. Spencer, 2002, private communication at an informational meeting at AFRL, Albuquerque, May 11.

Hegeler, F., C. Grabowski, and E. Schamiloglu, 1998, "Electron density measurementsduring microwave generation in a high power backward-wave oscillator", IEEE Trans. Plasma Sci. **26**, 275.

Hendricks, K. J., et al., 1996, "Extraction of 1 GW of rf power from an injection locked relativistic klystron oscillator," *Phys. Rev. Lett.*, **76**, 154; and references therein.

Hendricks, K. J., et al., 1998, IEEE Trans. Plasma Sci. **NS-26**, 320.

Hendricks, K. J., 2002, private communication at an information meeting at AFRL, Albuquerque, May 11.

Hess, M., 2002, "Green's Function Analysis of Bunched Charge-Particle Beams" (Ph.D. Dissertation, Massachusetts Institute of Technology), May 17.

Hess, H., and C. Chen, 2000, "Confinement criterion for a highly bunched beam," Phys. Plasma **7**, 5206.

Hess, M., and C. Chen, 2002a, "Equilibrium and confinement of bunched annular beams," Phys. Plasmas **9**, 1442.

Hess, M., and C. Chen, 2002b "Beam confinement in high-power periodic permanent magnet focusing klystrons," Phys. Lett. **A295**, 305.

Hess, M., and C. Chen, 2003, manuscript in preparation.

Otto, G., C. Chen, V. Roytershteyn, and R. Pakter, 2001, "Intense corkscrewing and wobbling elliptic beams in a piecewise uniform magnetic focusing field," to appear in Proc. 2001 Accel. Conf.

Pakter, R., and C. Chen, 2000a, "Electron beam halo formation in periodic permanent focusing klystron amplifiers," IEEE Trans. Plasma Sci., **28**, 502.

Pakter, R., and C. Chen, 2000b, "Cold-fluid equilibrium for a corkscrewing elliptic beam in a variable focusing channel," Phys. Rev. **E62**, 2789.

Scheitrum, G., 2002, "SLAC 95-GHz klystrino experiment," presented at MURI Review, Monterey, CA, April 28.

Sirigiri, J. R., K. E. Kreischer, J. Machuzak, I. Mastovsky, M. A. Shipiro, and R. J. Temkin, 2001, "A Photonic Band Gap Resonator Gyrotron", Phys. Rev. Lett. **86**, 5628.

Smirnova, E. I., and C. Chen, 2000, *Photonic Bandgap Structure Simulator (PBGSS) User's Manual*, Version 0.1, October 15 (MIT, Plasma Science & Fusion Center, Cambridge, MA).

Smirnova, E. I., and C. Chen, 2001, *Photonic Bandgap Structure Simulator (PBGSS) User's Manual*, Version 1.0, June 7 (MIT, Plasma Science & Fusion Center, Cambridge, MA).

Smirnova, E. I., C. Chen, M. A. Shapiro and R. J. Temkin, 2002, "Simulation of photonic band gaps in metal rod lattices for microwave applications," J. Appl. Phys. **91**, 960.

Sprehn, D., G. Caryotakis, E. Jongewaard, and R. M. Phillips, 1998, "Periodic permanent magnetic development for linear collider X-band klystrons," Proc. XIX International Linac Conf. (Argonne National Laboratory Report ANL-98/28), p. 689.

Sprehn, D., G. Caryotakis, E. Jongewaard, R. M. Phillips, and A. Vlieks, 2000, "X-band Klystron development at the Stanford Linear Accelerator Center," in *Intense Microwave Pulses VII*, edited by H. E. Brandt, SPIE Proc. **4031**, 132.

Stringfield, R. M., 2002, Los Alamos National Laboratory, private communication.

List of Researchers Supported under
AFOSR Grants No. F49620-00-1-0007

Mr. Ronak Bhatt	Graduate Student MIT Physics Department
Dr. Chiping Chen	Principal Research Scientist MIT Plasma Science and Fusion Center
Prof. John A. Davies	Physics Department Clark University Visiting Scientist MIT Plasma Science and Fusion Center
Mr. Yoel Fink	Graduate Student MIT Material Science and Engineering Department Degree Received: Ph.D Date: May, 2000 Current Position: Assistant Professor Dept. of Material Science and Engineering MIT
Mr. Mark Hess	Graduate Student MIT Physics Department Degree Received: Ph.D Date: May, 2002 Current Position: Postdoctoral Research Associate MIT Plasma Science and Fusion Center Part-Time Faculty Departments of Physics, Clark University and Worcester Polytechnic Institute
Mr. Garrett Otto	Graduate Student MIT Physics Department
Dr. Renato Pakter	Visiting Scientist MIT Plasma Science and Fusion Center
Dr. Bao-Liang Qian	Visiting Scientist MIT Plasma Science and Fusion Center
Miss Evegenya Smirnova	Graduate Student (Research tools only) MIT Physics Department

List of 2000-2002 Publications on
Coherent Structures and Chaos in Beam Plasmas*

***Research supported by**
AFOSR Grant No. F49620-00-1-0007

Refereed Journals:

1. M. Hess and C. Chen, "Confinement criterion for a highly bunched beam," Phys. Plasmas **7**, 5206 (2000).
2. J. A. Davies and C. Chen, "Stimulated radiation from spatiotemporally gyrating relativistic electron beams" Phys. Plasmas 7, 4291 (2000).
3. M. Hess and C. Chen, "Beam confinement in high-power periodic permanent magnet focusing klystrons," Phys. Lett. A295, 305 (2002).
4. M. Hess and C. Chen, "Equilibrium and confinement of bunched annular beams," Phys. Plasmas **9**, 1442 (2002).
5. E. I. Smirnova, C. Chen, M. A. Shapiro, and R. J. Temkin, "Simulation of photonic band gaps in metal rod lattices for microwave applications," J. Appl. Phys. **91**, 960 (2002).
6. J. Zhou, B. L. Qian, and C. Chen, "Chaotic particle motion and beam halo formation induced by image-charge effects in a small-aperture alternating-gradient focusing systems," submitted to Phys. Rev. Lett. (2003)

Conference Proceedings:

1. M. Hess and C. Chen, "Bunched annular beam equilibrium and confinement," *Intense Microwave Pulses VIII*, edited by H. E. Brandt, SPIE Proc. **4371**, 57 (2001).
2. J. A. Davies and C. Chen, "Influence of velocity spread on cyclotron masers driven by spatiotemporally gyrating electron beams," *Intense Microwave Pulses VIII*, edited by H. E. Brandt, SPIE Proc. **4371**, 39 (2001).
3. G. Otto, C. Chen, V. Roytershteyn, and R. Pakter, "Intense corkscrewing and wobbling elliptic beams in a piecewise uniform magnetic focusing field" to appear in Proc. 2001 Part. Accel. Conf. (2001).

US Patent Applications:

1. Chen, C., M. A. Shapiro, J. R. Sirigiri, and R. J. Temkin, "Vacuum Electron Devices with a Photonic Bandgap Structure," US Provisional Patent Application, Serial No. 60/278,131, March 23, 2001.
2. Chen, C., M. A. Shapiro, J. R. Sirigiri, E. I. Smirnova, and R. J. Temkin, "Photonic Bandgap Structure Simulator," US Provisional Patent Application, Serial No. 60/298,434, June 15, 2001.